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Using high-resolution simulated climate projections in forest process-based modelling

J.H.N. Palma[a,*], R.M. Cardoso[b], P.M.M. Soares[b], T.S. Oliveira[a], M. Tomé[a]

[a] Forest Research Centre, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017, Lisboa, Portugal
[b] Instituto Dom Luiz, CGUL, Universidade de Lisboa, Lisboa, Portugal

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ABSTRACT

Forest management decisions often rely on forest growth process based models. These models require climate data at a time-scale and a time-frame that is frequently not available in the area of interest. With the purpose of evaluating the use of modelled climate as a replacement for observational data, we compared the performance (efficiency, precision and bias) of a forest growth process based model (3-PG) when the inputs of the observational climate data were replaced by modelled climate data. Based on previous research, we focused on two promising regional climate models: 1) the Regional Atmospheric Climate Model (RACMO) and 2) the Weather Research and Forecast Modelling System and Program (WRF).

Results suggest that when using simulated climate data there are minor losses of performance in the forest growth model predictions with a general growth overestimation, with RACMO providing the best results. A deeper analysis suggests that improving the temperature accuracy of the model will reduce the overestimation of the predictions.

The use of simulated climate data with RACMO and WRF is therefore recommended when observed climate is scarce or inexistent. The use of these datasets can certainly widen the usage of forest growth process based models, improving the support for decision-making in forest management, especially when considering climate change, one of the cornerstones for which modelled climate is developed.

1. Introduction

Process based models (PBMs) offer insights into tree growth that is useful for both forest management and applied research (Korzukhin et al., 1996; Johnsen et al., 2001). Their use and application has increased in recent years due to the need to consider productivity under climate change, becoming an important tool to support adaptive forest management and planning (Bugmann and Trasobares, 2013; Garcia-Gonzalo et al., 2014; Mcmurtrie and Wang, 1993; Valentine et al., 1997).

In order for PBMs to project reliable estimates of forest growth, the model parameters need to be calibrated and the estimates need to be validated against observed data, using both physical drivers (soil and climate) and tree growth measurements. Although computers and software capacities allow a wide use of PBMs, the availability of climate data remains a challenge. Typically, climate data for modelling is collected from a meteorological station located near the place where the tree measurements are gathered (e.g. an installed meteorological station). In its absence, e.g. due to lack of budget, data from the nearest available climate station is used.

Climate data is frequently difficult to retrieve, in particular when no meteorological station has been installed and measurements from meteorological station networks have to be used. Even when data from these networks exist, other problems persist such as a lack of climate measurements during certain time periods, the distance between the climate station and the tree measurements is too far, or the climate data is too expensive to buy, especially in the case of models requiring daily weather data for long periods (e.g. to simulate the growth of slow growing trees).

The development of regional climate models (RCMs) in the recent decades has provided meteorologists with a powerful tool to characterise past and future, and regional to local, climates (Giorgi and Mearns, 1999; Laprise, 2008; Rummukainen, 2010). Although able to represent physically consistent regional and local atmospheric circulations, their accuracy is highly dependent on the quality of the boundary conditions, the physical parameterisations (Evans et al., 2013; Flaounas et al., 2011; Liang et al., 2008), the horizontal and vertical resolutions used (Boberg et al., 2010; Rauscher et al., 2010; Soares et al.,

* Corresponding author at: Forest Research Centre, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017, Lisboa, Portugal.
E-mail address: joaopalma@isa.ulisboa.pt (J.H.N. Palma).

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2012a,b,c), on the horizontal domain size (Colin et al., 2010) and on the error measures selected to analyse their performance (Soares et al., 2015, 2017).

The European climate community has, in recent years, been involved in the construction of regional climate datasets for the whole continent at increasingly higher resolution. The latest project, EURO-CORDEX (Jacob et al., 2014), is a consortium of several climate centres which has performed regional climate simulations for a common European domain at 12 km and 50 km resolutions for present and future climates. The compliant set of simulations includes:1) a hindcast simulation, forced by ERA-Interim reanalysis (Dee et al., 2011), for the 1979–2009 period, representing a synchronized present climate dataset, thus suitable for describing the actual climate and be fully evaluated against observations at the full range of output temporal and spatial scales; 2) a historical simulation forced by a free running Global Circulation Model (GCM), for the period 1971–2000, therefore only statistically comparable to observations; and (3) future climate simulations, covering the period from 2006 to 2100, following the Representation Concentration Pathways (RCP) future emissions scenarios. Kotlarski et al. (2014) analysed the near surface temperature and precipitation from the hindcast simulations and detected a cold and wet bias in almost all of the European domain and in most of the seasons; nevertheless, the different RCMs were able to capture the spatial and temporal variability of the European climate.

Similarly to the EURO-CORDEX project, a set of 9 km resolution simulations for the Iberian Peninsula has also been performed by the University of Lisbon using the Weather Research and Forecast (WRF; Skamarock et al., 2008) regional climate model. The hindcast simulation has been evaluated against point observations for maximum and minimum temperatures and precipitation in Portugal (Soares et al., 2012a,b,c) and Iberian solar irradiance (Magarreiro, 2016), as well as gridded datasets for Iberian precipitation (Cardoso et al., 2013; Rios-Entenza et al., 2014), and onshore and offshore wind (Nogueira et al., 2018; Soares et al., 2014). In all cases remarkably good results were obtained. Additionally, these hindcast simulation results were used for fire propagation studies (Sá et al., 2017) and investigations on the climatic cooling potential for Iberian buildings (Campaniço et al., 2016).

This work explored the potential of using such simulated climate data to predict forest growth.

The main objective was to evaluate the performance of process based model estimations when replacing observed climate data with simulated climate data. If the performance observed previously using simulated climate datasets can be transposed to forest modelling applications, it would widen the range of application of both simulated climate datasets and forest growth models to a greater extent in two important research areas. One is the calibration and validation of forest PBMs where currently scarce or no weather measurements are available, and another is the combination of both PBMs and modelled climate data considering future scenarios, to deepen the knowledge for strategic decisions for adapting the sustainable forest management in the future (e.g. Garcia-Gonzalo et al., 2014; Palma et al., 2015).

2. Materials

To compare the performance of real and simulated climate data we used a forest growth PBM where the evaluation consisted of the comparison of predicted forest growth against tree measurements when using 1) observed climate data and 2) regional climate simulated data. As the resolution of the simulated datasets is getting finer, we further assessed if there was an advantage of having such finer resolution by testing simulated data from a grid coordinate a) near the observed weather station and b) near the tree measurements.

2.1. Forest growth process based model (PBM)

The model 3-PG - Physiological Principles in Predicting Growth – is a simple, process based model (PBM) developed with the intention of bridging the gap between the simpler empirical models and the more complex physiological based ones, giving stand-level information of interest for forest management (Landsberg and Waring, 1997; Sands and Landsberg, 2002). The model is well-documented, the code is freely available and it has already been calibrated for *Eucalyptus* plantations in Portugal (Fontes et al., 2006). It is a forest stand level model that works on a monthly time step where the main outputs are the biomass values for stem, foliage and roots, but it also estimates stem volume, basal area, stand density, mean stem diameter at breast height, mean annual stem volume increment, available soil water, stand transpiration and leaf area index.

The 3-PG implemented in Excel (with integrated visual basic for applications), version 2.7 was used (available at http://booksite.elsevier.com/9780123744609/?ISBN=9780123744609) with the parameter values for eucalyptus stands in Portugal from Fontes et al. (2006).

2.2. Tree measurements and soil data

Field data was collected from 1988 to 2013 from different experimental plots located in different regions representing wide climate and soil variation in the eucalyptus expansion region in Portugal (Fontes et al., 2006; Oliveira, 2015). All the plots were of first rotation stands of non-clonal *Eucalyptus globulus* Labill. The trees were measured for diameter at breast height while height was measured on at least the dominant trees. When necessary, tree height was estimated with the equation from Soares and Tomé (2002). Volume was calculated using the equations from Tomé et al. (2002) while aboveground biomass and biomass per tree component (stem wood, stem bark, branches and leaves) were estimated using the equations developed by Antonio et al. (2007). A total of twelve sites were used (Supplementary material #1 - Fig. 1). Tree measurements covered a wide range of stand ages, densities and site indices (dominant height at age of 10). A total of 2682 trees in 125 plots were measured between 1988 and 2013 (Supplementary material #1).

For each site, a soil pit was dug and profiled to collect information on soil texture, depth, available soil water and other soil-related data needed for the 3-PG model (see details in Oliveira, 2015).

2.3. Observed climate data

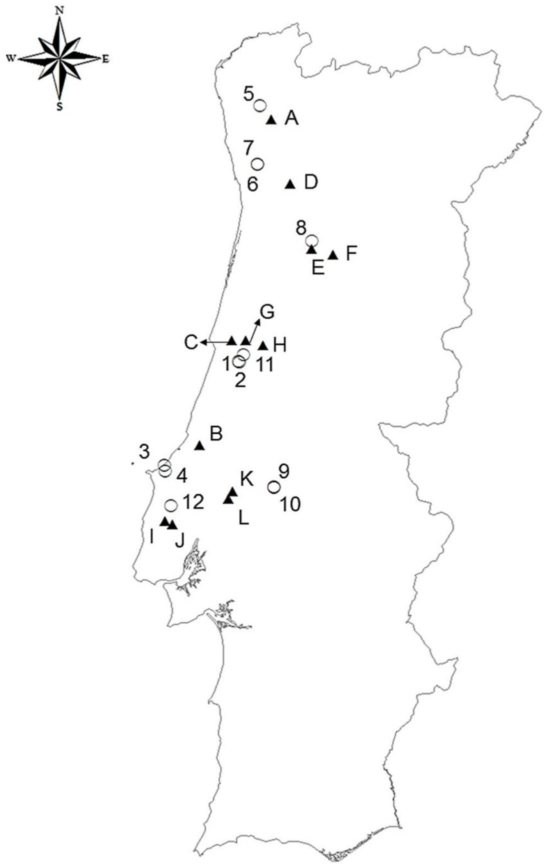
The climate data used, covering the growth period of the stands, was partially collected from SNIRH (Sistema Nacional de Informação de Recursos Hídricos http://snirh.pt/) and partially acquired from the Instituto Português do Mar e da Atmosfera (IPMA) (Fig. 1).

Climate data from 1988 to 2004 and from 2009 onwards was acquired from IPMA, while climate data from 2005 to 2009 was collected from SNIRH. SNIRH had a network of climate stations covering Portugal mainland and all data is freely available; however from 2009 to 2014 the stations stopped working due to a lack of budget, so data from 2009 onwards was completed with data purchased from IPMA.

The nearest stations for each site was chosen to collect climate data (Supplementary Material #1 and Table 1) that included monthly mean minimum and maximum daily temperatures, accumulated precipitation, number of days with rain > 1 mm (wetdays) and frost days and yearly solar radiation (Supplementary material #2).

2.4. Simulated climate data – regional climate models

The climate data used included the highest resolution climate regional simulation dataset available covering all of Iberia, and the KNMI RACMO model results generated in the framework of the EURO-CORDEX project, at 12 km resolution. The higher resolution regional climate dataset was produced using the Weather Research and Forecasting (WRF) model, at 9 km, forced by the ERA-Interim



label	Climate stations (▲)
A	1 (IPMA)
B	2 (IPMA)
C	3 (IPMA)
D	4 (IPMA)
E	5 (SNIRH)
F	6 (IPMA)
G	7 (SNIRH)
H	8 (IPMA)
I	9 (SNIRH)
J	10 (IPMA)
K	11 (SNIRH)
L	12 (IPMA)
label	**Tree plots (○)**
1	C020
2	C021
3	C026
4	C058
5	QP09
6	VL21
7	VL33
8	1
9	2
10	3
11	4
12	5

Fig. 1. Location of plots and weather stations – adapted from (Oliveira, 2015).

Table 1
Name and location of the climate stations used in tree measurement plots.

CODE	Name	Lat (N)	Lon (W)	Source	Plot ID
1	Braga	41.55	−8.40	IPMA	QP09
2	Alcobaça	39.53	−8.97	IPMA	C026,C058
3	Montemor-o-Velho	40.18	−8.72	IPMA	C020,C021
4	Vilar de Luz	41.15	−8.25	IPMA	VL21,VL33
5	São Pedro do Sul	40.75	−8.07	SNIRH	1
6	Viseu	40.71	−7.90	IPMA	1
7	Santo Varão	40.18	−8.60	SNIRH	4
8	Coimbra	40.15	−8.47	IPMA	4
9	Orjariça	39.06	−9.24	SNIRH	5
10	DoisPortos	39.04	−9.18	IPMA	5
11	Santarém	39.25	−8.70	SNIRH	2,3
12	Fonte Boa	39.20	−8.74	IPMA	2,3

reanalysis (Dee et al., 2011) for the 1989–2012 period. Both the setup details and the physical parameterisations selected can be viewed in Soares et al. (2017) and Cardoso et al. (2013).

In general, EURO-CORDEX 12 km regional climate model simulations provide higher daily precipitation intensities, which are completely missing from the global climate model (GCM) simulations. Soares et al. (2017) analysed the behaviour of the EURO-CORDEX models regarding the representation of precipitation over Portugal, showing that the KNMI RACMO model is the best performing model; this extends also to representation of European precipitation (Katragkou et al., 2015; Kotlarski et al., 2014; Prein et al., 2016). With regards to temperatures, the KNMI RACMO model compares well to other models for Iberia (Cardoso et al., 2018).

3. Methods

Having the original IPMA/SNIRH climate dataset as reference, data for the same time periods was extracted from the RACMO and WRF hindcast (synchronized present climate) datasets. Two sets of data were extracted; one considering the coordinates of the climate station (S) used, and the other one using the coordinates of the tree measurement plots (P) to check if the use of climate simulations near the measured sites would improve the PBM performance.

The 3-PG model was used with each of the datasets and its performance was assessed considering model efficiency (e_f), bias (M_r) and precision ($M_{|r|}$), calculated as follows:

$$e_f = 1 - \frac{\sum_{i=1}^{n} r_i^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \quad (1)$$

$$M_r = \frac{\sum_{i=1}^{n} r_i}{n} \quad (2)$$

$$M_{|r|} = \frac{\sum_{i=1}^{n} |r_i|}{n} \quad (3)$$

where r_i is the residual for observation *i*, y_i is either stem biomass (Ws), leaf biomass (Wl), root biomass (Wr), basal area (G) or volume (V) for observation *i*. $\bar{y}$ is the mean value of each of variables Ws, Wl, Wr, G or V. *n* is the number of observations for each of the variables Ws, Wl, Wr, G or V.

Efficiency, bias and precision were calculated for the results of the PBM using the three climate datasets.

Table 2
Forest growth model (3-PG) performance using observed and simulated climate data from RACMO and WRF datasets.

Variable	Reference	RACMO (S)	WRF (S)	RACMO (P)	WRF (P)
Model efficiency (e_f)					
Ww	0.93	0.92	0.77	0.87	0.80
Wl	0.91	0.84	0.77	0.90	0.80
Wr	0.44	0.38	0.32	0.40	0.33
V	0.88	0.79	0.69	0.82	0.71
G	0.95	0.89	0.81	0.91	0.83
average					
Average diff to reference		−0.06	−0.15	−0.04	−0.13
Mean value of the residuals (M_r) – Bias					
Ws	−1.58	−3.78	−8.56	−2.90	−8.54
Wl	0.10	−0.07	−0.47	0.00	−0.46
Wr	−9.67	−11.03	−14.01	−10.45	−13.85
V	−9.55	−13.55	−21.67	−11.85	−21.57
G	−0.16	−0.52	−1.39	−0.41	−1.41
Mean of the absolute value of the residuals ($M_{\|r\|}$) – Precision					
Ws	3.72	6.07	10.12	5.76	9.52
Wl	0.46	0.71	0.90	0.56	0.84
Wr	10.25	11.83	14.76	11.06	14.38
V	8.74	13.88	20.51	12.14	19.40
G	0.94	1.45	1.97	1.27	1.87

Reference: climate from observed climate in nearest station from tree measurements; RACMO and WRF: source models for simulated climate datasets. (S) is climate data retrieved for the coordinate near the climate station used in the reference while (P) is from the nearest coordinate of the plot where the tree measurements were made. Ww: Woody Biomass (Mg ha^{-1}); Wl: Leaves biomass (Mg ha^{-1}); Wr: Root biomass (Mg ha^{-1}); V: Volume (m^3 ha^{-1}); G: Basal Area (m^2 ha^{-1}).

4. Results and discussion

In this section, the main objective was to compare the performance of a forest process based model, when driven by observed or simulated climate data. To do so, an evaluation against tree measurements was performed using observed climate data and the datasets of simulated climate from WRF and RACMO.

The reference performance of 3-PG was the one achieved by the forest model with the observed climate data from the nearest climate station. Unsurprisingly, this simulation had the highest efficiency, the lowest bias and the highest precision (Table 2).

By using simulated climate data, the efficiency of the PBM was reduced. However, this reduction was interestingly low indicating that the high quality of the regional climate data, as evidenced by Soares et al. (2012a,b,c), can be transposed to forest growth projections. For example, using RACMO data from the nearest station reduced the model efficiency from 0.93 to 0.92 (about -1.07%) in the estimation of stem biomass (Table 2), clearly suggesting that this type of simulated climate may be used where observed climate data is scarce or non-existent.

Between RACMO and WRF climate models, RACMO revealed better results in terms of forest PBM efficiency throughout all state variables. The average precision of the model was reduced by 4 and 15% when using the RACMO datasets near the plot and WRF near the climate station respectively (Table 2). Results with simulated climate data near the plots consistently outperformed those retrieved near the observation weather station, suggesting that higher resolution of the simulated datasets improves the quality of the climate representation for the forest growth simulations here envisaged, given that efficiency of the model was nearer the reference efficiency with closer coordinates to the trees.

In a deeper analysis, we noted that RACMO and WRF datasets have, in general, higher absolute values for bias and precision than the reference. However, there was an exception where simulated climate outperformed observed climate data; bias was reduced in the estimation of leaf biomass with RACMO-S and RACMO-P.

RACMO and WRF simulated climate data led to the overestimation of the stand variables (higher values in precision with lower bias - Table 2, Fig. 2). This overestimation of the predicted values when using simulated climate datasets can be explained by the slight, but persistent, higher minimum temperatures, lower maximum temperatures, lower number of frost days and higher values of precipitation and radiation obtained from RACMO and WRF (Supplementary material #3).

Both simulated climate datasets have this behaviour, but WRF had larger differences when compared to the reference climate data, which explains the difference in the efficiency, bias and precision of both datasets, with better results for the RACMO dataset (Table 2).

Although the 3-PG model is sensitive to rain, temperature differences can explain most of the differences found when using the simulated climate datasets. Photosynthesis is temperature-dependent and exhibits a temperature optimum. Eucalyptus growth rates increase with increasing temperatures until the optimum temperature is reached, at which the species growth rate is maximum. Above this temperature the growth rate decreases and becomes zero. The growth rate is also zero below a minimum temperature. The 3-PG temperature thresholds for *Eucalyptus globulus* were set to 6 °C for the minimum, 16 °C for the optimum and 40 °C for the maximum (Fontes et al., 2006).

Simulated minimum temperatures from both RACMO and WRF were higher than the reference while maximum temperature values were lower (Supplementary material #3). This means that the simulated temperature remained near the optimum temperature and, consequently, the growth rates remained at a higher level, leading to an overestimation of the predicted stand variables.

Furthermore, radiation seemed to be consistently higher in the simulated datasets, which was consistent with fewer rain days (lower cloudiness). Being a direct input to photosynthesis, excess of radiation may also be a source for the general overestimation of the forest growth. However, summer radiation overestimation may not lead to a linear biomass growth rate because summer is when most of water stress hampering the potential for growth occurs. This may pose questions if future uses of simulated weather data is used for studying growth under irrigation conditions. However, this was not the case of the current plots where tree measurements were made.

Nevertheless, the overall stand biomass overestimation, in comparison to the reference, was very low, especially when using RACMO climate data near the plot coordinates (Fig. 2– Linear RACMO P), suggesting that this dataset is the best option to use when observed climate data is scarce or non-existent for the studied locations and when using monthly mean values.

5. Conclusion

Previous studies in the climate research community have shown that simulated climate data have good performance when compared to observed climate data (Katragkou et al., 2015; Kotlarski et al., 2014; Soares et al., 2012b, 2015). This work envisaged the use of such datasets in terrestrial ecosystem modelling, in particular for the forestry community by using a forest growth process based model, comparing simulations using observed climate with simulated data to project forest growth.

Results have shown that datasets of simulated climate can have minimal reduction of performance; the best results reduce overall model efficiency by only 4% with the use of the RACMO model dataset. RACMO also produced less bias and higher precision compared to the WRF model. Furthermore, this work emphasized that there is an advantage to using higher resolutions of climate dataset simulations as coordinates near the tree measurements produced higher model efficiencies, less bias and more precision, in both RACMO and WRF datasets.

Therefore, regional climate simulated data could allow the

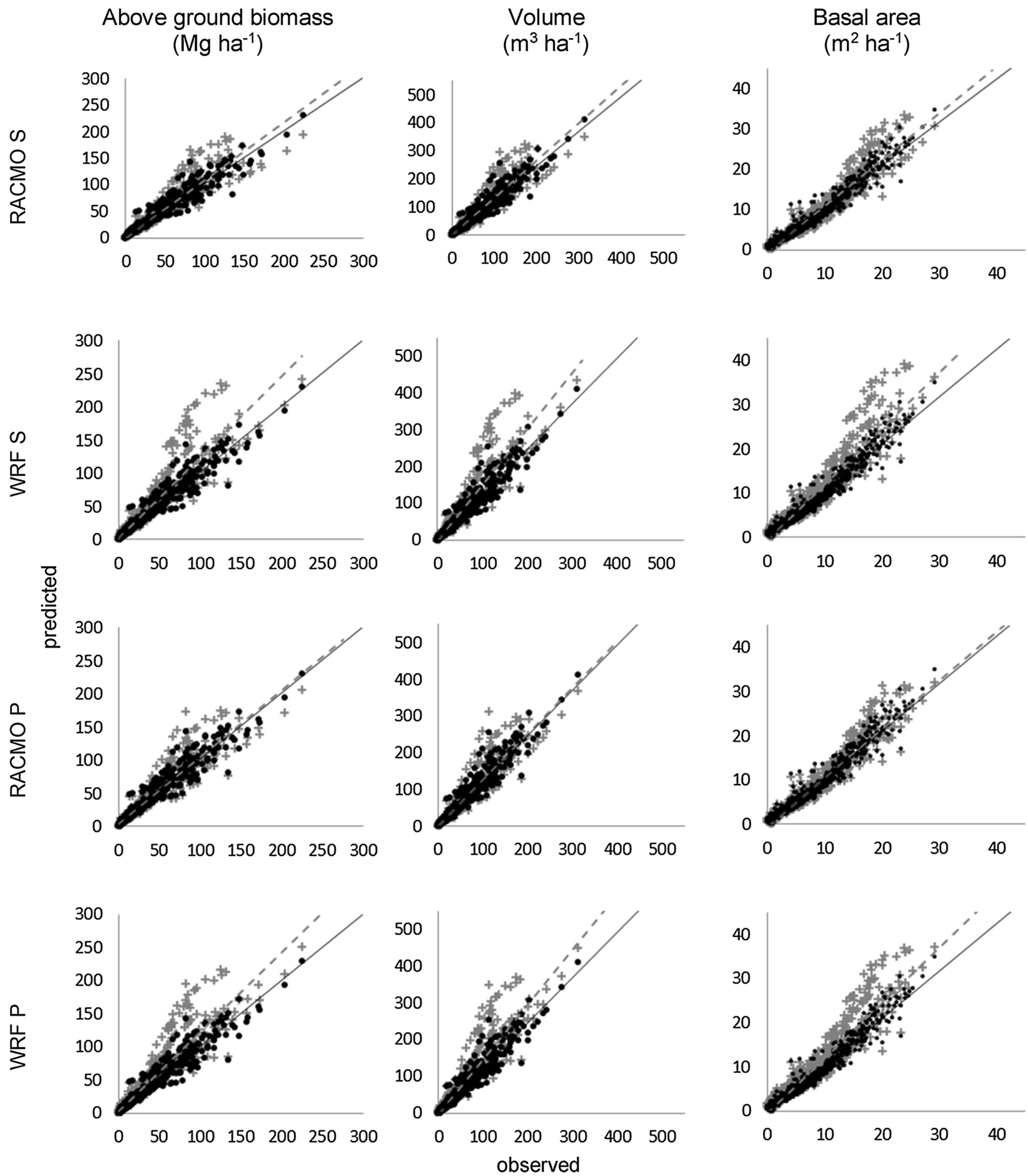


Fig. 2. Observed and predicted above ground biomass, volume and basal area with simulations considering observed climate data from nearest station (•, continuous trendline), and with simulated climate data (+, dashed trendline) from models RACMO and WRF for coordinates near the observed climate station (S) and the tree plot (P).

geographical extension of the application of forest growth process based models to much broader regions, especially to areas where weather stations do not exist or are scarce. However, such wider use requires more exhaustive comparison as for a particular location, the prediction of different climate variables may have a better response from alternative climate models (Stéfanon et al., 2015; Zhao et al., 2012). Although this study provided an example with eucalyptus, the mechanistic concept of process based models allows us to foresee good perspectives for using these kind of models, also for other species and other land uses (e.g. agriculture or agroforestry), with simulated climate data, because this can be a scarce resource, especially with models requiring daily time series (Luedeling et al., 2016).

It is also noticed that simulated datasets show a high degree of synchrony with measured data, both in absolute values and also in correct timing (e.g. precipitation in Supplementary material #3) suggesting that the use of simulated climate data could be also used for calibration of forest growth process based models. Simulated climate data do not emulate the annual variation in growth, however, even if the medium/long term simulations of growth are very good.

Despite the interesting quality of the simulated data, we found that the climate models can be improved in some aspects. For example, thermal amplitude is crucial for modelling photosynthetic activity. We

identified that a small decrease of maximum temperature and/or increase of minimum temperature has a high impact on productivity. As this study is not exhaustive in terms of exploring different climate datasets, further studies could focus on different climate data sources, providing a different overview and suggestions for improvement in the climate models. Nevertheless, we can conclude that EURO-CORDEX is a good source for regional climate data retrieval to be used for forest modelling, but the correct model evaluation is a key step in its use. Furthermore, using EURO-CORDEX data can extent the use of the forest growth models to envisage climate change assessments in future research.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agrformet.2018.08.008.

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